19. CONTROL VALVE: HOT GAS FAST RESPONSE

J. T. Hollis, A. B. Killebrew, and J. M. Smith
McDonnell Douglas Astronautics Company—West
McDonnell Douglas Corporation

ABSTRACT

This control valve was a key component in the jet interaction (JI) control of the UpSTAGE missiles which were flown in 1972. The vehicle was an elliptic cone which provided space at the extreme aft end for the JI control system. This system was mechanized to provide maneuverability of the vehicle. The moments necessary for pitch, yaw, and roll control were provided by a fast-response system of 10 nozzles located around the aft periphery of the vehicle. Each nozzle was fitted with a control valve which regulated the flow of gases from a solid propellant gas generator to the nozzle.

The control valve functioned in an on-off mode. The prime requirement on the valve design was the 10-millisecond response time. However, the most difficult problems in the development resulted from the vibration and acceleration effects on the valve operation and also from the particulate matter in, and the chemical composition of, the propellant exhaust, which the valve controlled and by which the valve was operated.

This paper, after briefly describing the valve's physical configuration and presenting a pictorial schematic of its arrangement, discusses several of the more interesting and challenging problems encountered during the development testing.

The discussions include the effect on valve performance and integrity by the material and shape of the upstream gas manifolds. Some do's and don'ts for designing valves for very severe vibration and high acceleration environments will be presented. A description of the destruction which resulted from internal parts impacting their stops at a hundred thousand g's, as well as the solution for this problem, also will be presented. Interesting and novel solutions to the anticipated erosion and thermal problems associated with the hot gas will be included.

Several performance oddities are disclosed along with their reasons, such as why the valve's response time decreased when rapidly cycled several times.

SUMMARY

Design of a warm gas control valve is reviewed outlining the problems posed by the requirement for extremely fast response combined with a severe environment and a hot, dirty, and corrosive operating fluid.

INTRODUCTION

The jet interaction (JI) models of the UpSTAGE vehicle are controlled by a set of 10 nozzles, 4 or 5 of which are discharging warm gas from a solid propellant gas generator into the boundary layer to provide large control forces. The flow through the nozzles is controlled by three-stage, warm gas control valves operating in a bistable mode. In addition to controlling the thrust vector, the valves regulate the gas generator pressure by the number of valves open at any time. In order to satisfy the response and stability requirements of the vehicle, the valves were required to have a response time of 10 milliseconds or less.

Acknowledgement is made to Moog Inc., Western Development Center, Monterey Park, California, who developed this valve under subcontract for the UpSTAGE program.

The JI control valve is an electrically commanded three-stage valve consisting of a pilot, an intermediate, and a main stage. A schematic of the valve is shown in Figure 1. The first stage is operated by a flat-faced magnet, and the second and third stages are operated by gas pressure. Each stage is a poppet-type stage, balanced for poppet areas and utilizing a 2:1 area ratio for operation. Springs are provided to insure proper poppet position at startup but are unnecessary for actual operation of the second and third stages. A novel feature is the provision for operation of the valve with cold gas by pressurization through the vent port. This enables each stage to be exercised without application of pressure to the normal inlet port.

Stringent requirements with regard to valve response, weight, high pressure, leakage, valve position indication, and restricted envelope dictated a careful analysis of the available schemes to accomplish the task of designing the valve. The response of the valve was considered to be the most important specification parameter. A reliable, fast-acting position indicator, minimum weight, low peak wattage demand, and low leakage rates were other essential prerequisites governing valve design. The severe valve response requirements over a broad spectrum of operating conditions were achieved by a three-stage valve.

A summary of valve specification requirements is given in Table 1.

The pilot stage is a conventional solenoid-operated poppet. The poppet is of balanced design, biased by a spring to port the incoming gases to the intermediate stage. The construction of the intermediate stage is essentially identical to the pilot stage. Gas pressure is used to shift the poppet spool of the intermediate stage to either fill or dump the main stage pintle control cavity. Amplification effect of the intermediate stage allows use of a relatively small pilot stage solenoid, with low power demands, to operate the valve. The pilot and intermediate stages were arranged on the valve structure to be in the axis of least g-sensitivity.

The main stage of the valve is balanced by use of an integral pintle support and a guide member. There are many advantages to this approach, the most significant being that the control cavity volume back of the pintle is reduced to the minimum allowable in this design. This small control volume contributes directly to the fast valve action. The pintle support reduces very effectively the variation in forces on the pintle due to the wide excursion of operating pressure range. The valve body is made from a titanium alloy, primarily for weight considerations. This material, however, is not an ideal material for sliding applications and therefore the pintle support member is used for guiding the pintle. The clearances of the parts are arranged to insure that the pintle slides on the support and not on the housing. In addition, the hollow support provides a space isolated from the warm gas, for packaging of the pintle closing spring, electrical suppression circuits components, and the indicator switch system.

In the pressure off, power off, or solenoid deenergized condition, the valve is closed and the main pintle is pushed against the seat by a spring. The intermediate stage poppet for the initial no-pressure case is shifted to close its vent port by a small bias spring so that the incoming pressure is directed to the main stage control cavity, insuring its closed position. The deenergized pilot stage is in the vent closed position ready to admit the gas to the large end of the intermediate stage.

With the solenoid energized, the armature overcomes the spring and friction forces to shift the poppet to close off the incoming pressure source and vent the large end of the intermediate stage overboard. With this end of the intermediate stage vented, the pintle shifts position due to the pressure acting on the opposite end of the intermediate poppet. This closes off the valve inlet pressure and connects the main stage pintle control cavity to the overboard vent. As soon as the control cavity pressure decays sufficiently, the pintle starts opening the main valve cavity.

Table 1

VALVE SPECIFICATION SUMMARY

Operating Fluid	Solid propellant GG combustion gas Temperature – 2,650°F (1,460°C) maximum Specific heat ratio – 1.29 Molecular weight – 19.3 No heavy abrasives or magnetic particles
Flow	7.4 lb/sec (3.36 kg/sec) at 3,250 psi (2,240 N/cm^2) inlet
Inlet pressure	2,050 to 4,600 psi (1,410 to 3,160 N/cm^2)
Pressure drop (inlet or outlet)	500 psid (345 N/cm^2) at full flow
Operating duration (flight)	1.5 sec minimum
Response time	0.010 sec maximum, 0.005 sec minimum
Cycle rate	50 Hz
Leakage at 4,600 psi (3,160 N/cm^2)	
External	0.001 sccs maximum
Main stage internal	0.05 lb/sec (22.6 gm/sec) maximum
Pilot stages internal	0.02 lb/sec (9.1 gm/sec) maximum
Shelf life	1 year
Cycle life	
At 0 psi (0 N/cm^2)	2,000 cycles
At 4,600 psi (3,160 N/cm^2)	300 cycles
At flight conditions	75 cycles
Weight	3.43 lb (1.56 kg) maximum
Electrical inputs	
Minimum	2.0 amp at 25 vdc
Maximum	2.4 amp at 30.3 vdc
Burst pressure	9,200 psi (6,320 N/cm^2) minimum

The selection of materials for all components of the assembly was based on engineering practice and backed up by past experience. Material combinations used in this design have been successfully applied in previous designs and are compatible with the valve operating media. Titanium alloy, TI-6AL-4V, in the annealed condition was selected for the valve housing because it offered light weight, high strength, and low thermal conductivity. Due to the short valve operating duration, minimal temperature rise in the body was expected; however, based on test results it was determined that a zirconia coating would be required inside the body to insulate it from the high temperatures.

The main stage pintle is made of Hastelloy-C and 17-4 which were inertia-welded together. Dry film lubrication Microseal is applied to all surfaces of the pintle. The intention here is to reduce friction on the inside diameter of the pintle where it runs on the chrome-plated pintle support surface. The pilot stage and intermediate stage of the valve are constructed of identical materials except the pilot stage has a Rene 41 poppet and the intermediate stage has a 440C stainless steel poppet. These poppets seat on Monel K500 material. The bushings that support the seats are 416 stainless steel. The springs used in these stages are of 302, 17-4, or 304 stainless steel and are sufficient for the duration of the valve operation. Hydrogen-annealed C-1018 carbon steel is used in the solenoid construction. The solenoid is encased by a cover and for additional corrosion protection both the armature and the electromagnet are nickel plated. The solenoid coil is wound with a heavy coated magnet wire on a bobbin. By using epoxy, the coil is potted into the steel core of the solenoid body.

The main seat material and configuration are identical to those of several other warm-gas valves. The seat material used is tantalum tungsten which is a ductile material with a high melting point of 5,550°F (3,030°C) and a very low coefficient of thermal expansion. Dimensional changes induced by heating are insignificant because of the low thermal expansion coefficient. This material is compatible with the specified propellant. The seat is pressed into the outlet passage of the plenum chamber against a shoulder. In addition to this press fit, the seat is also held at all times either by the pintle or the inlet pressure forces. The available force margin to translate the pintle is large enough to overcome the environmentally induced loads and still provide a comfortable design margin of safety. The minimum available pintle opening and closing forces are 430 lb (195 kg) and 630 lb (285 kg), respectively, at 1,800-psia (1,240 N/cm^2) inlet pressure.

The position indicator on the valve is a single-pole switch which indicates the position of the main pintle. This switch is electrically closed when the valve main poppet is in the open position and is electrically open when the valve main poppet is in the closed position. The switch is located in the free volume behind the main pintle and is not subjected to hot gas conditions. Basically, the switch is constructed of a rod connected to the main pintle which slides on stationary flexible beryllium copper springs. Sections of the moving rod are appropriately coated with nonconductive materials in order to make or break contact as required. The concept was selected over other schemes for speed of operation. minimum bounce time, and good vibration and shock capabilities.

The ammonium perchlorate base propellant used to supply the operating gas poses some problems to valve design. Initially, the gas generated is of the order of 2,600°F (1,430°C) which will melt or soften many materials. Secondly, there is a high percentage of hydrochloric acid generated which, at the high temperatures, not only can attack valve materials but also will form undesirable compounds on reaction with system materials. Finally, there is a high carbon content especially at the lower temperatures which can clog passages and bind moving parts. All these problems were encountered in the valve development.

Early in the development testing, the valve performance was to suffer from a large amount of contamination. The contamination appeared to be particulate carbon bound together with a sticky material and was of a sufficient consistency to stop the first stage movement. Chemical analysis of the binder material showed it to be ferric chloride. It seemed likely that this was being generated by

the reaction of the hot hydrochloric acid in the grain combustion products with the steel gas generator case and the manifolds. These surfaces were subsequently protected with a coat of flame sprayed zirconia which reduced the generation of the ferric chloride to acceptable levels. Although considerable amounts of carbon remained in the valve after the test, it was presumed that this was largely generated during the tailoff as it had little effect on performance. As a precaution, fine mesh screen filters were installed at the inlets to the first and second stages.

An unexpected source of difficulties was the impact load generated when the third stage impacted on its stops. This impact, resulting from the pintle moving 0.25 in. (0.64 cm) in approximately 2 ms caused failure of position transducer attachments, buckling of the pintle itself, and even a tension failure of a stainless-steel 10-32 screw from the inertia of the screw head when undergoing the deceleration of the pintle. It was necessary to redesign the pintle to incorporate an inertia-welded 17-4 stainless-steel skirt to the Hastelloy-C poppet to prevent buckling of the skirt. The original switch configuration with the contact fingers mounted on the moving part had to be redesigned to put these fingers on the stationary part since the impact loads neatly sheared off the fingers from their own weight. Significantly, the self-induced shock loads on the valve body were more severe than the environmental criteria.

The unusually high environmental acceleration and vibration loads (see Figure 2) on the valve posed some interesting problems. Magnet forces had to be high, not only to overcome the g loads and friction effects induced by these loads but also because of the high spring return forces. Consideration had to be given to deflections, particularly if the parts became warm. Initially, the vibration problem was considered secondary and only normal good design practice was considered necessary. On testing, however, problems developed, particularly with the magnet stage. The armature of the magnet, being cantilevered on its shaft, broke, moved on its press fit, gouged the aluminum cover, and exhibited other undesirable actions until tamed by a new design incorporating a large press fit area and support around the armature periphery by the cover. An indication of the level of vibration, again self-induced by the jet interaction process, was that the testing facility was not able to supply the environment with its largest equipment in one pass, having to split the spectrum into three parts which were run separately. The high acceleration levels caused test equipment problems as well as some unexpected instrumentation anomalies due to the high g forces. For example, a few inches of grease in an instrumentation pressure line was enough to offset the line pressure under acceleration until the grease burned out, resulting in some perplexity during data reduction until the phenomenon was identified.

The magnet design, which had been used successfully on other components, allowed the armature to tilt in the housing. While the force levels and response were adequate during the initial testing, the armature failed under vibration. In an attempt to correct this failure, the armature shaft was strengthened and the armature was constrained so as to move parallel to the magnet face. It was then discovered that the available magnet force had diminished substantially. Testing of the original configuration revealed that the original armature motion consisted of a tipping sequence in which one edge of the armature would contact the magnet first, followed by the opposite side. This mode yielded substantially higher magnet forces than the constrained motion. In the final version, the armature shaft diameter was increased and the armature supported by its edge on the inside of the housing. This configuration successfully passed the vibration testing. A number of problems were encountered with the armature shaft attachment. Swaging and electron-beam welding were both tried unsuccessfully to preclude shifting of the armature on the shaft and finally the original press fit with larger bearing and interference areas solved the problem.

The original design, allowing the warm gas to impinge directly on the titanium body, proved inadequate, the first test resulting in a burn-through on the inlet neck and enough softening to allow body distortion. A 20-mil coating of zirconia, flame sprayed on the interior of these passages, proved adequate to keep body temperatures within acceptable levels. The main stage pintle had to be

thickened to prevent its distortion and five of six vent holes in the top of the pintle had to be removed to keep circulation of the warm gas from destroying the seal inside the pintle. The other seals performed quite well and in most cases were intact after operation and the inevitable heat soak after test completion.

Although the Viton seals performed quite well in the elevated temperature regimes, some difficulty was experienced with the slipper seals which protected these seals. The U cross-section seal on the main pintle trapped gas pressure underneath itself and bound up the main pintle. This was alleviated by grooving the sides of the seal to allow pressure to escape. A more obscure problem developed with the slipper seal on the first stage pintle nearest the magnet. When the magnet was energized, the poppet moved forcing the slipper seal against the side of the groove. At the same time, the poppet was unseated allowing pressure to build up in the adjacent chamber. Since the slipper seal was blocking flow into the O-ring groove, gas was able to leak past the slipper into the magnet chamber and blow the armature away from the magnet, resulting in anomalous operation of the valve. This condition was cured by venting the magnet chamber.

In spite of the testing problems, the valve development was very successful. A measure of this was the necessity to impose a minimum operating time on the vendor of 5 ms from the original requirement of 10 ms or less. Both vehicle flights were successful and the valve subsequently is being used in another test program where fast response is a prime requirement. A photograph of the valve is shown in Figure 3.

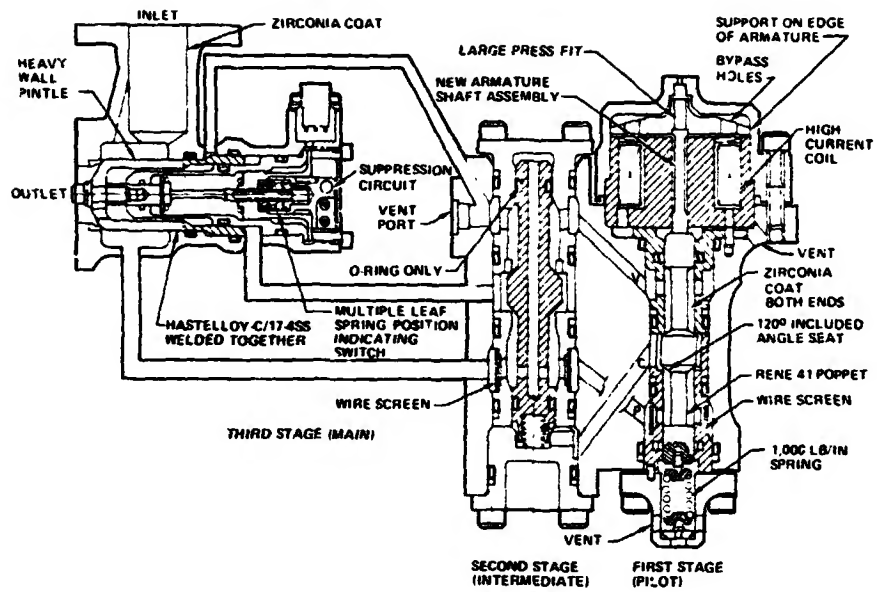

Figure 1.- Jet interaction control valve final configuration.

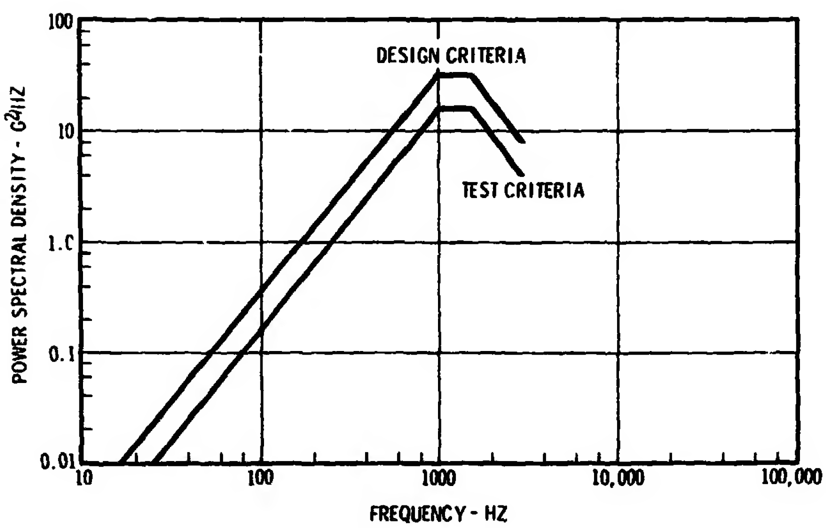

Figure 2.- Random vibration criteria for valve design and test.

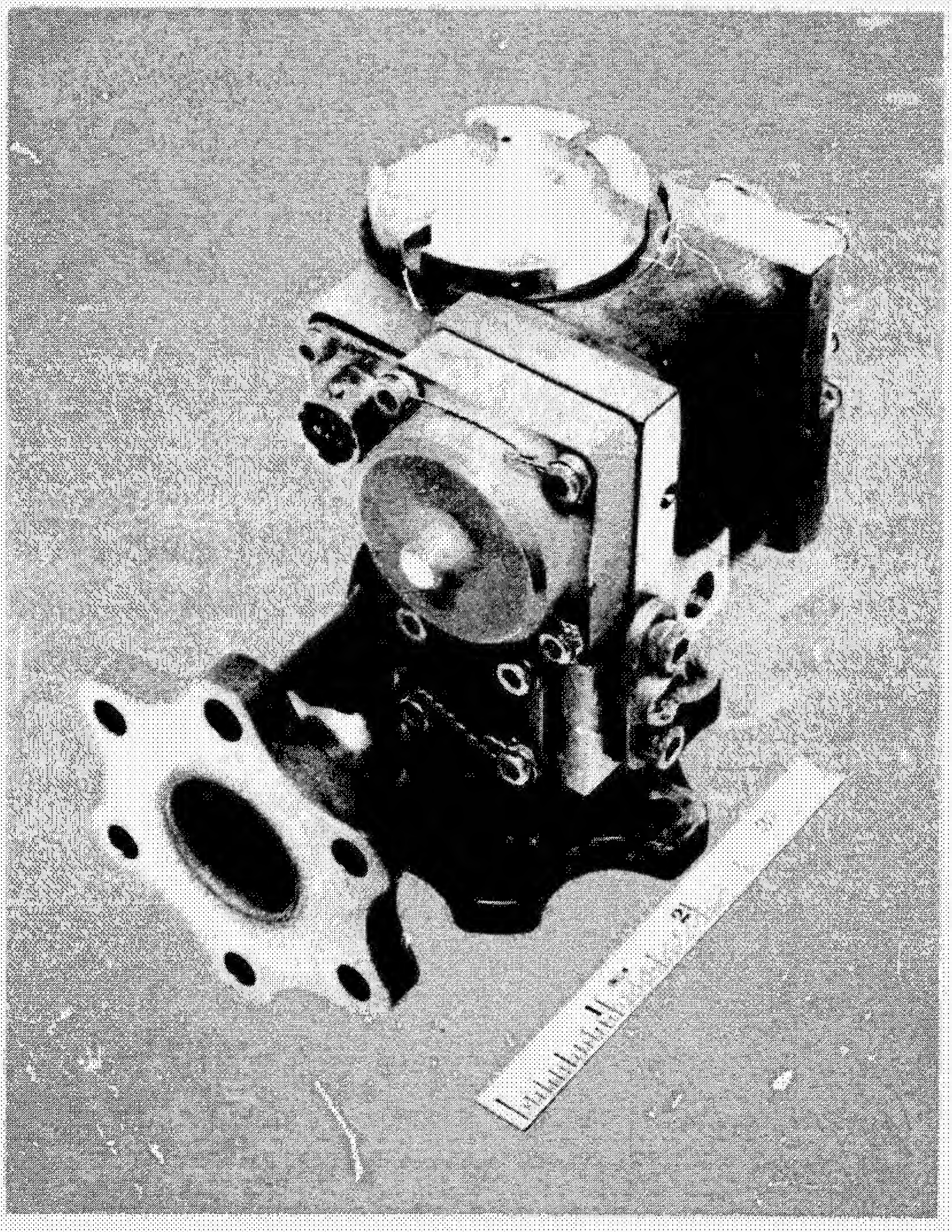

Figure 3.- Warm-gas valve.